Predicting regime shifts in flow of the Colorado River

Subhrendu Gangopadhyay[1] and Gregory J. McCabe[2]

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[1] The effects of continued global warming on water resources are a concern for water managers and stake holders. In the western United States, where the combined climatic demand and consumptive use of water is equal to or greater than the natural supply of water for some locations, there is growing concern regarding the sustainability of future water supplies. In addition to the adverse effects of warming on water supply, another issue for water managers is accounting for, and managing, the effects of natural climatic variability, particularly persistently dry and wet periods. Analyses of paleo-reconstructions of Upper Colorado River basin (UCRB) flow demonstrate that severe sustained droughts, and persistent pluvial periods, are a recurring characteristic of hydroclimate in the Colorado River basin. Shifts between persistently dry and wet regimes (e.g., decadal to multi-decadal variability (D2M)) have important implications for water supply and water management. In this study paleo-reconstructions of UCRB flow are used to compute the risks of shifts between persistently wet and dry regimes given the length of time in a specific regime. Results indicate that low frequency variability of hydro-climatic conditions and the statistics that describe this low frequency variability can be useful to water managers by providing information about the risk of shifting from one hydrologic regime to another. To manage water resources in the future water managers will have to understand the joint hydrologic effects of natural climate variability and global warming. These joint effects may produce future hydrologic conditions that are unprecedented in both the instrumental and paleoclimatic records. **Citation:** Gangopadhyay, S., and G. J. McCabe (2010), Predicting regime shifts in flow of the Colorado River, *Geophys. Res. Lett.*, *37*, L20706, doi:10.1029/2010GL044513.

1. Introduction

[2] The Upper Colorado River basin (UCRB), that part of the Colorado River basin that is upstream from the stream gauge at Lees Ferry, Arizona (Figure 1), generates approximately 90 percent (%) of the total flow of the Colorado River basin, and supplies water and hydropower for much of the southwestern United States (US). In addition, the UCRB supplies water to northern Mexico. Because of recent drought, the balance between water supply and demand in the Colorado River basin has become a concern [*Hoerling and Eischeid*, 2007; *McCabe and Wolock*, 2007]. The allocation of water from the Colorado River is determined using flow data from the wettest period of the 20th century and is one of the wettest of the last several centuries [*McCabe and Wolock*, 2007]. Natural flow variability produced the high-flow period used for the allocation of water from the Colorado River basin. The current levels of water allocation may be difficult to sustain given natural climatic variability and the potential effects of global warming.

[3] *Enfield and Cid-Serrano* [2006] developed a method to calculate the probability of future decadal-to-multi-decadal (D2M) regime shifts. They illustrate their technique using a time series of the Atlantic Multi-decadal Oscillation (AMO) and produce a graph that shows the risk of shifting from one AMO regime to another given the length of time in a current regime. *Enfield and Cid-Serrano* [2006] further indicate that the method is robust and can be applied to any sufficiently long time series that exhibits substantial D2M variability.

[4] Because the UCRB is the primary water supply for the southwestern United States (US) and the time series of UCRB flow indicate D2M variability [*McCabe et al.*, 2007], the method presented by *Enfield and Cid-Serrano* [2006] is applied to paleo-reconstructed time series of water-year flow for the UCRB. Paleohydrologic reconstructions provide robust information regarding the hydrologic state of basins – dry or wet, particularly in the southwestern United States. *Gangopadhyay et al.* [2009] analyzed seven paleohydrologic reconstructions for the UCRB (at Lees Ferry, AZ) and found that, although the reconstructed streamflow magnitudes differ among the reconstructions, all seven reconstructions were synchronous in their determination of the dry and wet spell lengths [see *Gangopadhyay et al.*, 2009, Figure 4]. In this paper, we analyze wet and dry spell statistics from a set of paleohydrologic reconstructions [*Gangopadhyay et al.*, 2009]. The objective is to compute the risk of shifting to a new regime of UCRB flow given the length of time in a current regime. These results provide a tool for water managers, and others, who are involved with activities in the UCRB that are influenced by future climate regime shifts. In addition, this study provides an illustration of real-world application of information regarding D2M climate variability.

2. Paleohydrologic Streamflow Data

[5] A set of nine paleohydrologic reconstructions of annual streamflows (starting in 1400) for the Lees Ferry gauge was developed by *Gangopadhyay et al.* [2009] (Figure 2). The methodology for developing the reconstructions is based on the K nearest neighbor (KNN) nonparametric method [*Gangopadhyay et al.*, 2009]. The method used tree ring chronologies from the period 1400–2005 in the UCRB region and naturalized streamflow for the period 1906–2005 at the Lees Ferry, Arizona gauge on the Colorado River to develop annual streamflow ensembles for this gauge for the 1400–2005 period. Detail of the reconstruction methodology is described by *Gangopadhyay et al.* [2009]. The nine member

[1]U.S. Bureau of Reclamation, Denver, Colorado, USA.
[2]U.S. Geological Survey, Denver, Colorado, USA.

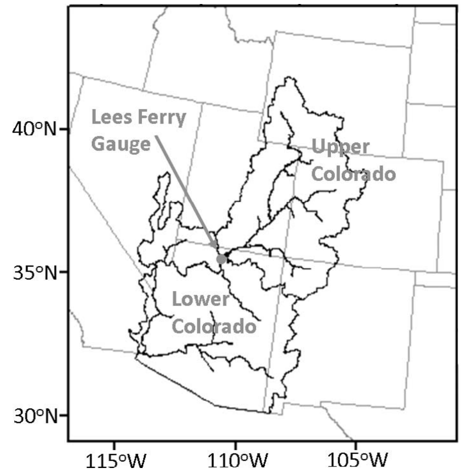

Figure 1. Map of the Colorado River basin.

ensemble used in this study is the ensemble mean flow from the nine reconstructions for the 1400–1905 period, and naturalized flow from the 1906–2005 period [*Gangopadhyay et al.*, 2009]. The basis for the nine reconstructions is the combination of three weighting schemes – (i) a bisquare weight (BSW), (ii) an inverse distance weight (IDW), and (iii) a 'one over *K*' weight (OKW), and three ending years in the tree-ring chronology data – 1997, 2002, and 2005. These nine ensemble members are labeled using the weighting scheme abbreviation and ending year of tree-ring chronology. For example, BSW1997 implies that the reconstruction was done using the bisquare weight function and that chronologies extend up to 1997. Thus, we had nine flow time series for the period 1400–2005 which were used in the analysis. Because we are interested in analyzing how D2M signals modulate dry and wet spells in the UCRB, each time series was filtered using a low-pass filter [*Kaylor*, 1977] to retain frequencies in the time series that were equal to and slower than 0.1 cycles per year. Using nine flow reconstructions provides confirmation of the robustness of paleoclimate reconstructions of streamflow, and the use of non-parametric methods to reconstruct the flow provides a means to realistically constrain the range of extreme dry and wet periods [*Gangopadhyay et al.*, 2009].

3. Methodology

[6] In this study, a regime (or interval) is defined using filtered time series with variability higher than 10 years removed (i.e., variability at frequencies up to 0.1 cycles per year was removed). Intervals are then defined by periods of successive zero crossings of the filtered time series. The length of intervals (wet – above zero crossing or dry – below zero crossing) was computed by counting the number of years in each interval for each of the nine paleohydrologic ensembles. The paleohydrologic ensembles of UCRB flow provide long records with multiple wet and dry intervals of varying length that are useful to determine statistical distributions of interval lengths (Figure 2).

[7] Probability projections of regime shift can be estimated by analyzing long-term hydrologic records. Paleohydrologic reconstructions derived from tree-ring data provide us with valuable multi-century flow time series that can be used to study historical dry and wet spells in the record. The assumption is that the time interval (T) between the two states, dry and wet, for the flow regime is a stochastic process [*Enfield and Cid-Serrano*, 2006]. Given a probability model for this stochastic process, P, we can construct useful probability projections for future realizations.

[8] The *first step* in the methodology is to develop a probability model to fit the distribution of regime shift interval, T. Distribution of spells or regime intervals have been widely modeled using the gamma family of distributions [*Salas et al.*, 2005]. In this study, we use a two-parameter gamma distribution with a shape and scale parameter to study regime shift [*Salas et al.*, 2005].

[9] Once the probability model (P) for T has been identified, it can be used to study regime shift in the conditional probability framework. For the *second step*, we assume that t_1 years have elapsed since the last regime shift, thus the conditional probability that a future regime shift will occur within a horizon of t_2 years, can be expressed as (equation (1)),

$$\begin{aligned} P(T > t_1 \cap T \le t_1 + t_2 | T > t_1) &= P(T > t_1 \cap T \le t_1 + t_2) \\ &\quad /P(T > t_1) \\ &= P(t_1 < T \le t_1 + t_2)/P(T > t_1) \\ &= (\Gamma[t_1 + t_2] - \Gamma[t_1])/(1 - \Gamma[t_1]) \end{aligned} \tag{1}$$

where $t = t_1 + t_2$ is the current climate regime interval and $\Gamma[t]$ is the two-parameter gamma cumulative distribution function (CDF) [*Enfield and Cid-Serrano*, 2006]. To ignore the probability space for intervals 1 year or less, a truncated gamma CDF was used in equation (1), $\Gamma[t] = \Gamma[t]/(1 - \Gamma[1])$, where $t > 1$. The variation of $P(T > t_1 \cap T \le t_1 + t_2 | T > t_1)$ as a function of t_1 (abscissa) and t_2 (ordinate) provides quantitative estimates of probability of regime shift [*Enfield and Cid-Serrano*, 2006].

[10] Results of fitting the two-parameter gamma distribution to the paleohydrologic ensemble members of flow

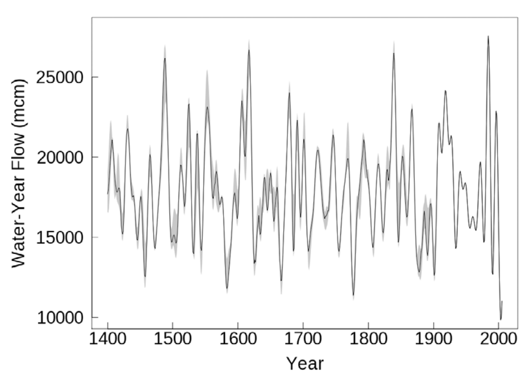

Figure 2. Time series of filtered reconstructed water-year flow at Lees Ferry [from *Gangopadhyay et al.*, 2009]. The gray shading indicates the maximum and minimum flows from the nine filtered times series and the black line indicates the median flow value from the nine filtered time series. The time series were filtered using a low-pass filter to retain frequencies in the time series that were equal and slower than 0.1 cycles per year.

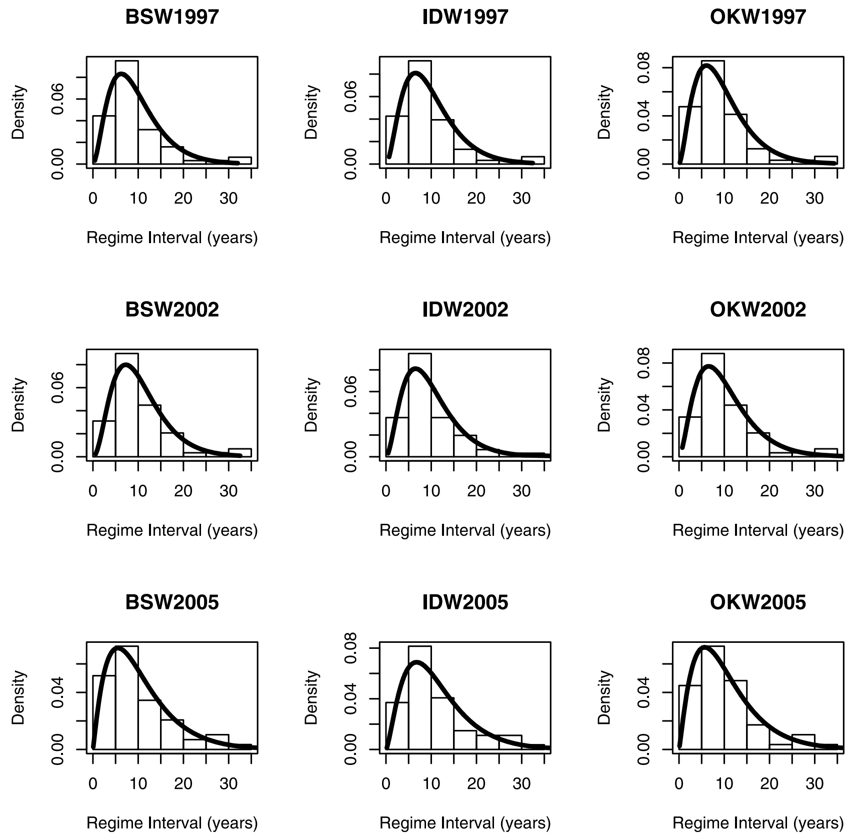

Figure 3. Two parameter gamma probability density function (PDF) of regime interval distribution for the nine ensemble members.

(step one) and using the fitted probability model to estimate the probabilities of future risk projections (step two) are described in the following section.

4. Results and Discussion

[11] Figure 3 illustrates the distributions of flow intervals for the nine paleohydrologic ensembles and the interval distributions estimated using the two-parameter gamma distribution model. Table 1 lists the shape and scale parameters for the two-parameter gamma distributions fitted to the distributions of wet and dry intervals for the nine time series of reconstructed flow. Also listed are the mean shape and scale parameters for all nine cases. Each set of shape and scale parameters is similar and suggests similar regime interval statistics for each of the nine streamflow reconstructions. Kolmogorov-Smirnov (KS) tests were performed to test how well the distributions of regime intervals estimated using the two-parameter gamma distributions compared with the regime intervals computed using the reconstructed flow time series (Figure 3). The KS tests indicated no statistically significant differences (at $p \leq 0.05$) between the estimated distributions of regime intervals and the respective distributions computed using the reconstructed flow time series. These results indicate that the two-parameter gamma distribution methodology provides reliable estimates of the distributions of regime intervals.

[12] An uncertainty of this approach is the effect of non-stationarity on the gamma distributions. In this study it is assumed that the tree-ring data for 1400–2005 capture the responses to natural climatic variability (and non-stationarity over that period) and that the mean parameters of the fitted gamma distributions from the over 600-year record provide meaningful risk estimates. In addition to the uncertainty in the fitted distribution parameters, another source of uncertainty is related to the quality of streamflow reconstructions. To characterize the later, nine reconstructions are used to provide confidence intervals for the risk estimates.

[13] Figure 4 illustrates the risk of a future regime shift (as a percent) given the number of years since the last regime shift and a specified number of years into the future. These results were obtained using the mean scale and shape parameters of wet and dry regimes (Table 1) for all nine of the streamflow reconstructions. Figure 5 illustrates the dis-

Table 1. Shape and Scale Parameter for the Two-Parameter Gamma Distribution Fitted to the Nine Ensemble Members, and the Mean Parameters

Ensemble Member	Shape	Scale (years)
BSW1997	2.8572	3.3666
IDW1997	2.9002	3.4255
OKW1997	2.6974	3.5660
BSW2002	3.2650	3.2001
IDW2002	2.9280	3.3929
OKW2002	2.7680	3.7107
BSW2005	2.1176	4.9340
IDW2005	2.5171	4.4583
OKW2005	2.2007	4.7476
Mean	2.6946	3.8669

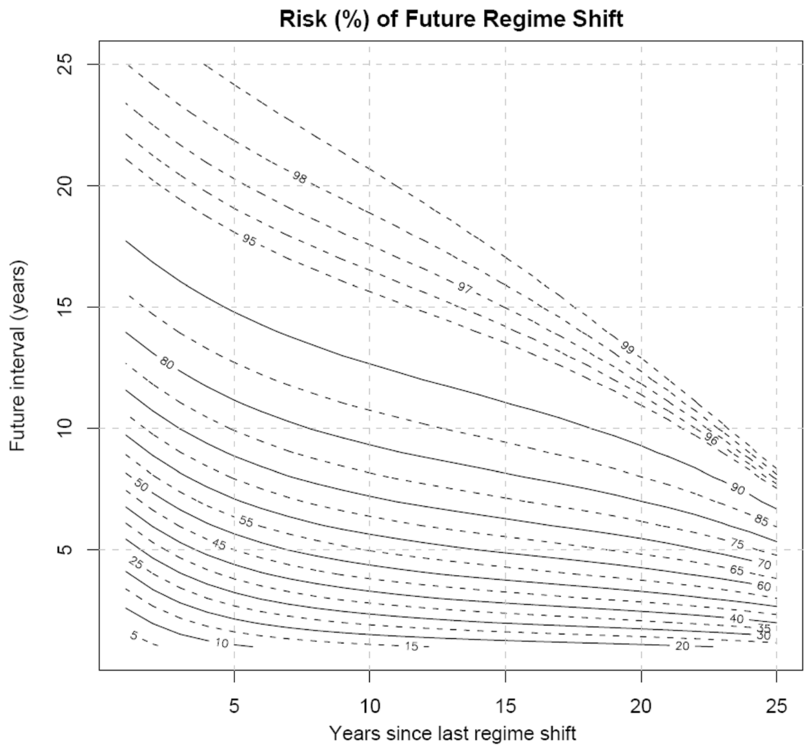

Figure 4. Distribution of the probability of a regime shift occurring within $t2$ future years (ordinate) given that $t1$ years (abscissa) have elapsed since the last regime shift. Based on the two-parameter gamma distribution with scale and shape parameters of 3.87 years and 2.69, truncated for $t1 + t2 > 1$ year.

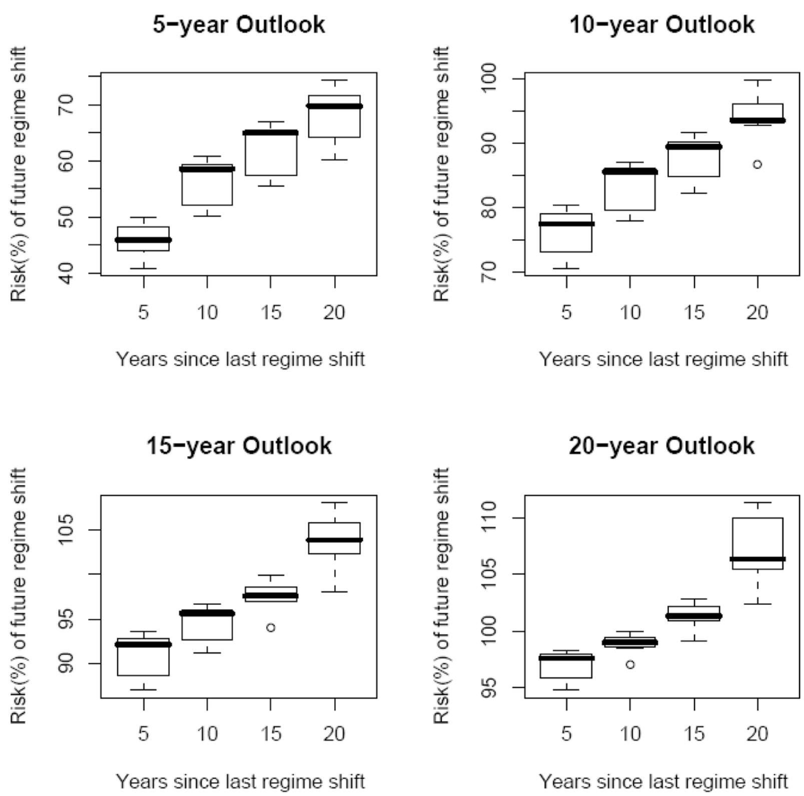

Figure 5. Boxplot of risk outlooks from the nine flow reconstructions. The boxes indicate the range between the 25th and 75th percentiles and the thick horizontal lines indicate median values. The thin horizontal lines connected by the vertical dashed lines indicate the approximate range between the 5th and 95th percentiles. The circles indicate outliers.

tributions of regime shift risk (as a percent) computed for each of the nine streamflow reconstructions and for 5-, 10-, 15- and 20-year future intervals.

[14] Understanding the low frequency variability of hydro-climatic conditions and the statistics that describe the low frequency variability can be useful to water managers by providing information about the risk of shifting from one hydrologic regime to another. For example, in 1925, the flow of the UCRB had been in a positive interval for 20 years. Based on analyses of the interval data for the nine paleohydrologic ensembles, the risk of a shift to an interval with below average flow during the following 5 years (Figure 5, top left) was about 60% to 80% (with a median value of about 70%) and the risk of a shift during the following 10 years (Figure 5, top right) was 93% to 99% (with a median value of 94%). A shift to a new interval actually occurred 6 years later. This result indicates that the estimated risks of a shift to a new flow regime could have been useful to water managers at that time, if they had been available.

[15] Figures 4 and 5 also can be used to estimate the likelihood of a regime change in UCRB flow for some specified number of years into the future. For example, since 1988 the flow of the UCRB has been in a regime of primarily below-average flow. From 1988 through 2006, below-average flow occurred for 13 years, and above-average flow occurred for only 6 years. If we assume that this period is a regime of below-average flow, then this regime has existed for 19 years. Based on Figure 4, the risk that there will be a regime change to a period of above-average flow by 2011 is approximately 65%, and the risk of a regime change to above-average flow by 2016 is almost 90%. Once the flow of the UCRB has shifted to a regime of above-average flow the risks of shifting to a drier regime also can be estimated using Figure 4. This tool has important implications for water resource managers in the Colorado River basin who are concerned with the effects of decadal to multi-decadal climate variability on water supply in the Colorado River basin.

[16] A number of studies have suggested that global warming is likely to result in decreased flow of the UCRB [*Hoerling and Eischeid*, 2007; *McCabe and Wolock*, 2007; *Barnett and Pierce*, 2009]. The results of this analysis (presented in Figures 4 and 5) represent the effects of natural climatic variability on the risk of moving into a wet or dry regime of UCRB flow. This analysis has not included the potential effects of climate change associated with global warming. Climate changes associated with global warming likely will add additional climate forcings that are not included in the streamflow statistics on which this analysis is based. Although the decadal to multi-decadal regime shifts indicated in this analysis will continue into the future, the resultant mean climate conditions for future wet and dry periods may be different than what has been experienced historically. For example, with increasing temperatures, and no concomitant increase in precipitation, the wet regimes in the future will not be as wet as they have been, and dry regimes will be drier than what has been experienced in the past due to increases in evapotranspiration. To manage water resources in the future water managers will have to understand the joint hydrologic effects of natural climate variability and global warming. These joint effects may produce future hydrologic conditions that are unprecedented in both the instrumental and paleoclimatic records.

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S. Gangopadhyay, U.S. Bureau of Reclamation, Denver Federal Center, Bldg. 67, PO Box 25007, Denver, CO 80225-0007, USA.

G. J. McCabe, U.S. Geological Survey, Denver Federal Center, MS 412, Denver, CO 80225, USA. (gmccabe@usgs.gov)